Maydestone Deep Energy Retrofit Monitoring Report

Submitted to:

Sacramento Municipal Utility District

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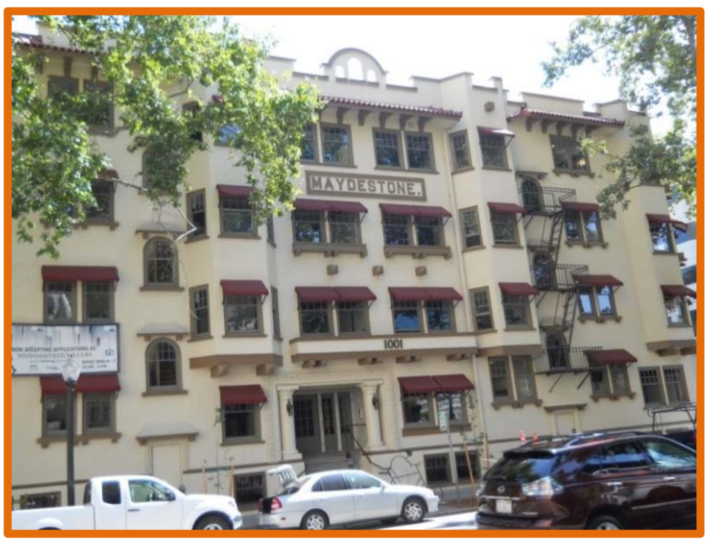

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About the Customer Advanced Technologies Program…

SMUD's Customer Advanced Technologies (C.A.T.) program works with customers to encourage the use and evaluation of new or underutilized technologies. The program provides funding for customers in exchange for monitoring rights. Completed demonstration projects include lighting technologies, light emitting diodes (LEDs), indirect/direct evaporative cooling, non-chemical water treatment systems, daylighting and a variety of other technologies.

For more program information, please visit:
https://www.smud.org/en/business/save-energy/rebates-incentives-financing/customer-advanced-technologies.htm

1. Executive Summary

SMUD worked closely with D&S Development on a Deep Energy Retrofit (DER) multi-family project located at the Maydestone building in downtown Sacramento. The DER project utilized envelope improvements, rooftop solar photovoltaic (PV) and thermal hot water, and ductless mini-split heat pumps (HP) in each apartment to achieve high energy savings. The objectives of this study were:

1. Electrical Energy Use
   a. What was the simulated annual energy use and electrical peak demand of this building prior to DER?
   b. What is the simulated annual energy use and peak demand after DER?
   c. What is the measured annual energy use and peak demand?

2. Space Conditioning System
   d. What is the measured performance of HPs under test weather conditions?
   e. How does this compare to simulated performance under similar weather conditions?
   f. How does this compare to published SEER and HSPF performance data?
   g. How effectively does space conditioning system maintain comfortable and/or consistent temperatures?
   h. How effectively does the air handling unit maintain consistent temperatures with and without the HP?

In addition, the following are addressed:

1. Measure the in-situ efficiency of a sample of ductless mini-split heat pumps,
2. Estimate the energy savings due to the high efficiency ductless mini-split heat pumps,
3. Leverage monitoring data to discern how performance of future projects can be improved.

To achieve the objectives, ADM Associates Inc. collected interval meter billing data from SMUD and performed long term monitoring of four apartments at the Maydestone building. These data were compared to the whole building simulations used to originally estimate project savings.

The whole building energy use and demand as simulated and metered is provided in Table 1-1. Table 1-2 and Table 1-3 summarize the study's findings on the mini-split heat pumps. These results and our findings are discussed in further detail in the body of this report.

Table 1-1 Energy Use and Peak Demand Estimates for Whole Building

	Annual Energy Use	Peak Demand
Pre DER Simulation	201,119 kWh	62 kW
Post DER Simulation	115,182 kWh	30.5 kW
Metered (Actual Weather)	135,252 kWh	29.1 kW
Metered (Normalized Weather)	134,585 kWh	23 kW
Ex Ante Savings	85,937 kWh	31.5 kW
Ex Post Savings	71,461 kWh	39.2 kW

Table 1-2 Mini-Split Equipment Performance by Apartment

Apartment #	Monitored Data Results SEER	Monitored Data Results HSPF	Manufacturer SEER	Manufacturer HSPF
1	17.9	11.1	23	11
2	20.8	8.5	23	11
3	1.7	0.6	23	11
4	31.7	13.6	21	11
Average[1]	26.25	11	22.5	11

Table 1-3 Energy Savings and Peak Demand Reduction Estimates for All Heat Pumps

Annual Energy Savings	19,824 kWh
Peak Demand Reduction	4.9 kW

Temperatures in the individual apartments varied considerably. Some of this can be attributed to periods when the units were unoccupied. Since no temperature complaints were relayed it is presumed the occupants were not uncomfortable.

Projects like DER have many sources of energy savings. Measurements to segregate the savings into each measure application can be invasive and costly. If the overall impact of the project is of most importance then savings analysis using billing meters is the most cost effective approach when a baseline exists. If no baseline exists then an energy simulation normalizing the post period to actual billing data is appropriate.

[1] Average does not include apartment # 3 for reasons discussed in Section 4 of this report.

2. Project Description

The Maydestone Apartment building is an historic 4-story apartment structure with daylit basement located in Sacramento, CA. There are eight apartments on each floor for a total of 32 apartments. They are studio and one bedroom apartments ranging in size from 233 sqft. to 693 sqft. There is a basement which contains a community room, fitness area, office area, individual storage units, restroom, and utilities. The house electric meter is for all loads not associated with the individual apartments and serves: inside and outside lighting, TV in community room, heating and cooling in community room, washers and electric dryers and electric water heating for washers, and the elevator. Recently the building received extensive retrofits intending to improve the building's sustainability through SMUD's Deep Energy Retrofit program (DER). While targeting deep energy efficiency retrofits, the final design of the building had to balance upgrades in materials and equipment with maintaining its historical elements. Ultimately the building incorporated the following energy efficiency upgrades in its final design:

1. Efficient ductless mini-split Heat Pumps (HP)
2. Addition of insulation to roof and walls
3. Cool Roof
4. Window film
5. Window awnings
6. Lighting fixtures: T-8, LED, CFLs
7. Elevator regenerative drive

In addition the building incorporated the following renewable energy systems:

1. Solar hot water heating for domestic hot water
2. Photovoltaic solar panels

The solar preheated water is distributed to the electric hot water heaters in each apartment which has a 20 gallon tank. The house has a 50 gallon water heater tank which is also supplied with solar pre-heated water. This tank is used for a couple of clothes washers and the bathrooms in the basement.

There are 66 solar photovoltaic (PV) panels on the roof and are approximately 18 square feet each. They are fixed position and face south. The rated output is 13.8 kW.

Special attention was given to evaluating the ductless mini-split heat pumps. One was installed in every apartment unit. The size (capacity) of the installed unit was dependent on the room size. Fujitsu models AOU9RLFW and AOU15RLS compressor units, 0.75 ton and 1.2 ton cooling capacity respectively, was mounted on the roof as shown in Figure 2-1 and Figure 2-3 . The indoor wall mounted fan units (see Figure 2-2) were Fujitsu models ASU9RLF and ASU15RLS. A set of solar thermal water heating panels are mounted on the south side of the roof and the back side can be seen in Figure 2-3.

Figure 2-1 Ductless Mini-Split Heat Pumps and Photovoltaic Panels on Roof

Figure 2-2 Ductless Mini-Split Air Handler in Apartment

Figure 2-3 Mini-Split Heat Pumps and Solar Thermal Water Heater Panels on Roof

ADM Associates Inc. was contracted by SMUD to evaluate the DER impacts on the whole building energy use. Specific attention was given to perform long-term monitoring of several apartments in order to quantify the impacts of the ductless mini-split heat pump measure. The specific objectives of the study were as follows:

1. Electrical Energy Use
    a. What was the simulated annual energy use and electrical peak demand of this building prior to DER?
    b. What is the simulated annual energy use and peak demand after DER?
    c. What is the measured annual energy use and peak demand?

2. Space Conditioning System
    d. What is the measured performance of HPs under test weather conditions?
    e. How does this compare to simulated performance under similar weather conditions?
    f. How does this compare to published SEER and HSPF performance data?
    g. How effectively does space conditioning system maintain comfortable and/or consistent temperatures?
    h. How effectively does the air handling unit maintain consistent temperatures with and without the HP?

In addition, the following are addressed:

1. Measure the in-situ efficiency of a sample of ductless mini-split heat pumps,
2. Estimate the energy savings due to the high efficiency ductless mini-split heat pumps,
3. Leverage monitoring data to discern how performance of future projects can be improved.

Electric Meters

Evaluation of whole building, solar PV generation and apartment energy use was conducted using SMUD's billing meters. There are 35 electric meters in the building. There is one for the energy use of the common area (house meter from SMUD), one for the energy production of the solar PV system, one for the surplus energy (house meter exported back to SMUD), and one for each of the 32 apartments. These meters are used for the determination of DER whole building loads, demands and savings. Hourly kWh (average hourly kW demand) data were provided for all the meters for the period from October 21, 2012 through October 20, 2013. Note that the sum of all 32 apartment meters was provided and only the four study apartment meters were provided individually. The meters are Landis & Gyr model Focus AXR-SD smart grid meters with interval kWh digital data recording. They are 0.5% accuracy classified with a typical accuracy of 0.2%.

Heat Pump Monitoring Approach

Since the majority of the energy efficiency retrofits targeted reductions in cooling and heating loads (or improving the efficiency of space conditioning equipment) significant resources were spent on characterizing the demands on, and performance of, the mini-split heat pump systems. Since each of the 32 apartments has its own mini-split heat pump, ADM monitored a representative sample of units (apartment on 1st floor =# 1, 2nd floor = #2, third floor = #3, and 4th floor = #4). The monitored apartments were chosen to represent the range of apartment square-footages, interior vs. exterior building placement, and also to capture a sufficient range of space heating/cooling loads. The following table (Table 2-1) lists each of the points monitored in this study.

Table 2-1 List of Monitoring Points Used in Maydestone Study

Parameter	Description	Units
Outdoor Air Temperature	Temperature of the rooftop outside air	^{o}F
Outdoor Air Relative Humidity	Relative humidity of the rooftop outside air	%
Apartment Power	Electric demand for sampled apartments	kW
House Power	Common area electric panel power	kW
Photovoltaic Generation	Electric power generated by roof-top PV panels	kW
Return Air Temperature	Temperature of the air returning to the sampled fan coils	^{o}F
Return Air Relative Humidity	Relative humidity of the air returning to the sampled fan coils	%
Supply Air Temperature	Temperature of the air supplied by the sampled fan coils	^{o}F
Fan Coil Unit Power	Electric demand of the sampled fan coil units	kW
Heat Pump Unit Power	Electric demand of the sampled heat pump units	kW
Ambient Weather	Weather data from a local weather station	Various

A description of the monitoring equipment and accuracies is provided in Appendix A.

3. DER Whole Building Energy Use

This chapter investigates the whole building impact of the DER Project at the Maydestone apartment building. No distinction is made between the energy efficiency measure contributions to the differences.

A simulation of the Maydestone retrofit was developed by Red Tape Express and provided to ADM at the beginning of this study. The simulation produces an 8,760 hourly output. Since no baseline metered data is available the modeled energy simulation is needed to provide the baseline or pre DER energy use of the building. The whole building energy use and demand as simulated and metered is provided in Table 3-1. The post DER simulation energy use is 17 percent lower than the metered energy use for the building. As such the ex post energy savings is estimated by adjusted downwards by the same percentage to account for model calibration. The ex post energy savings are 71,461 kWh which represents 35 percent of the baseline energy use. The demand savings was calculated similarly and is 39.2 kW

Table 3-1 Energy Use and Peak Demand Estimates for DER Whole Building

	Annual Energy Use	**Peak Demand**
Pre DER Simulation	201,119 kWh	62 kW
Post DER Simulation	115,182 kWh	30.5 kW
Metered (Actual Weather)	135,252 kWh	29.1 kW
Metered (Normalized Weather)	134,585 kWh	23 kW
Ex Ante Savings	85,937 kWh	31.5 kW
Ex Post Savings	71,461 kWh	39.2 kW

The monthly distribution of energy use for the common areas (house) and all the apartments is provided in Figure 3-1. The stacked bars in the chart are the total building electrical energy use by month. The energy use is highest in the winter at 15,762 kWh in January. The summer high use month is July at 12,323 kWh. Winter use is higher because solar water heating is supplemented by electric resistance water heaters in individual apartments and used for laundry in the common areas. Also heating the basement common areas using electric heat pumps may use more in the winter than cooling in the summers. Approximately 28 percent of the building energy use is for common loads and 72 percent is used in the 32 apartments. The data is for the one year period from October 21, 2012 through October 20, 2013.

Figure 3-2 shows an hourly profile on the SMUD peak system day in 2013, which occurred on July 3rd. The SMUD system load uses the left hand axis and peaks during the SMUD 4:00 P.M. to 7:00 P.M. summer peak period. The SMUD peak period is shown on the chart for reference and is the light yellow shaded area. The hourly demand for an average Maydestone apartment is 0.85 kW and peaks at 8:00 P.M. and uses the right hand axis. For comparison, the SMUD average multi-family demand is also charted. The typical multi-family customer demand peaked at 1.88 kW at 7:00 P.M. The Maydestone profile does not swing as much from night to day as a typical multi-family residence so is therefore less impacted by outdoor temperature.

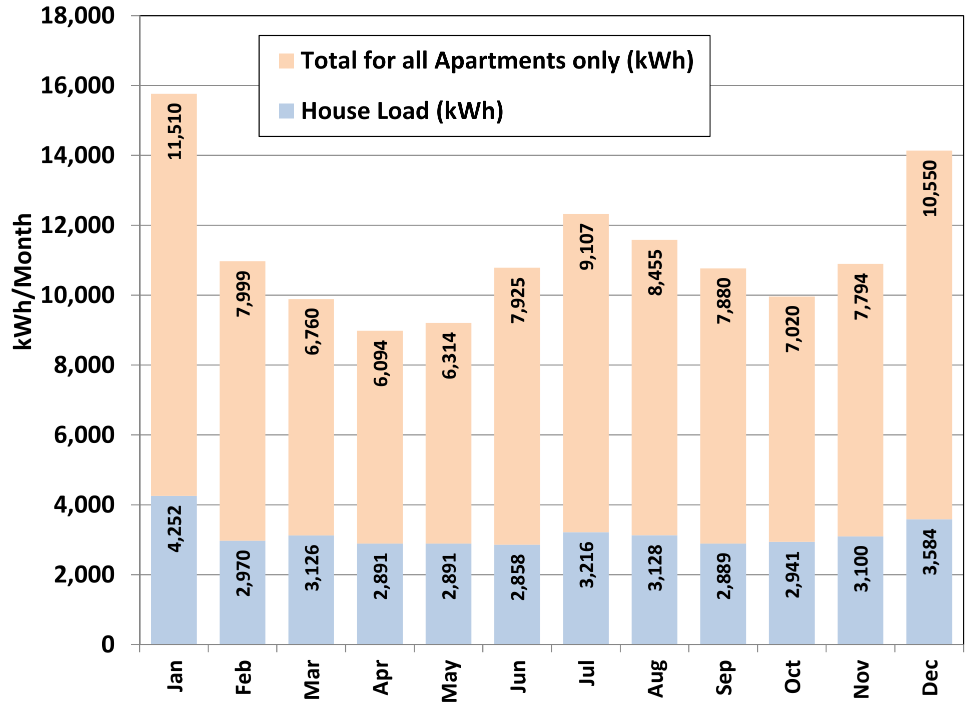

Figure 3-1 Monthly Apartment and House Common Area Energy Use

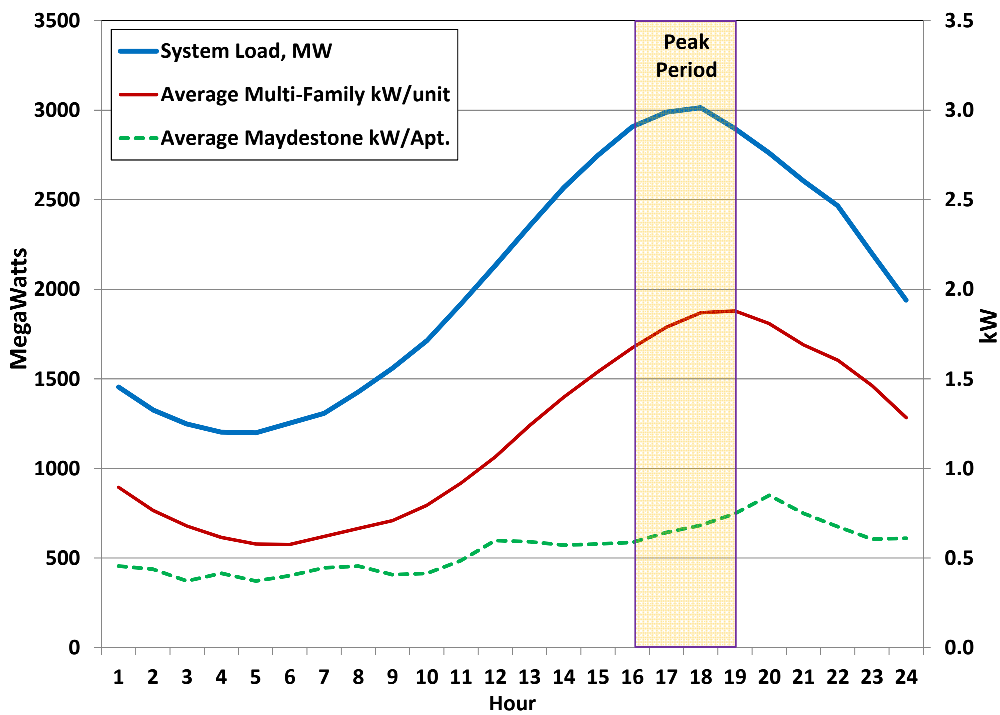

Figure 3-2 Peak Day Demand Profile Comparisons of System, Multi-Family, and Maydestone

Solar Photovoltaic System Power Generation

Some analysis of the solar PV system is also provided. A SMUD meter measures the AC (alternating current) output of the inverter for the PV system. The maximum output of the system as measured by the meter was 13.9 kW in June of 2012 which is close to system rating of 13.8 kW. The PV system supplies power to the apartment building common areas (house). A second SMUD meter, the house meter from SMUD, measures the electrical energy used by the common areas of the apartment building which is not supplied by the PV system. This house meter only measures energy from the utility grid. A third SMUD meter, the house meter to SMUD, measures the excess electrical energy generated from the PV system that is not used by the common areas of the apartment building and goes back to the SMUD utility grid. The power production profile of the PV system on an average summer (June through September) day is provided in Figure 3-3. During the day in the summer the PV system produces more power than the building common areas require and the house meter from SMUD falls to zero. The summer load on the house meter picks up before the end of SMUD's super peak period which ends at 7:00 P.M. On an average summer day the peak excess PV power sent back to the grid is 7.3 kW at 2:00 P.M. PDT. The maximum that has been sent back to the grid is 10 kW. A typical winter profile is provided in Appendix C.

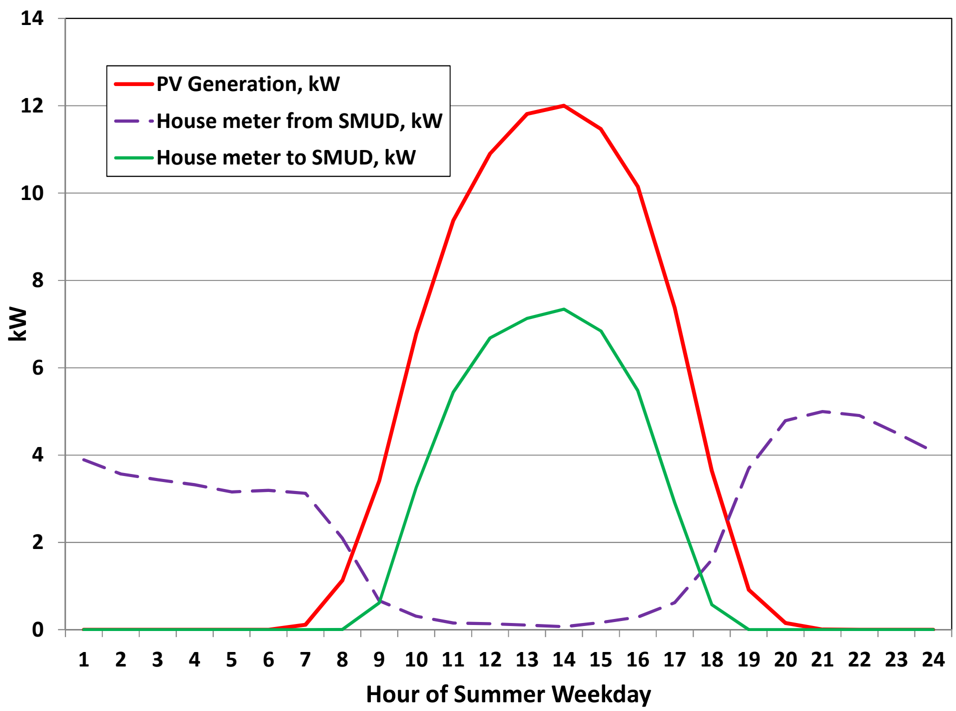

Figure 3-3 Average Summer Weekday PV Profile and House Meters

The monthly PV energy generation, house meter energy purchase from the utility, and house meter energy exported back to the utility are provided in Figure 3-4. The data is for the one year period from October 21, 2012 through October 20, 2013. On an annual basis, the energy produced by the PV system is almost as much as the energy the building house meter purchases from the utility or about 64% of the house load. The annual PV energy generation for the year of data was 24,388 kWh compared to 23,223 kWh system design and produces 18% of the total building energy use. The house common areas purchased 25,039 kWh from SMUD and used a total of 37, 846 kWh. During the year, 11,581 kWh was exported back to SMUD, which is 47% of the total PV production.

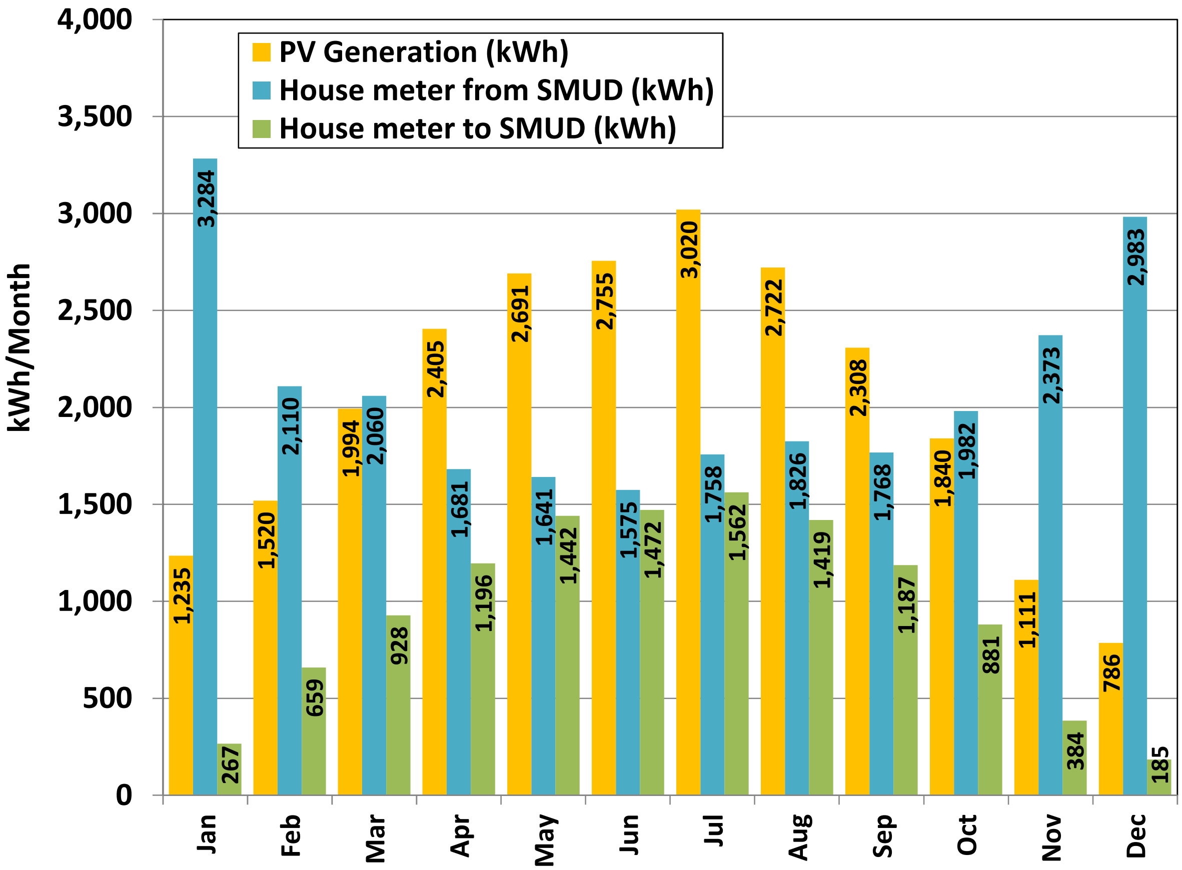

Figure 3-4 Monthly Metered Energy of PV Generation and House Meters

Heat Storm

The heat storm during the summer of 2013 occurred from June 28 through July 4, see Figure 3-5. Each day was 105 ºF or higher and peaked at 109 ºF on July 4th. Two of the seven days were weekend days and one was a holiday. SMUD's peak period is defined as occurring on a weekday, leaving four days from the heat storm that are analyzed as peak days. The SMUD system peak occurred on Wednesday July 3rd and was 3,014 MW. The chart shows the dramatic increase in SMUD's system peak for the heat storm versus the days leading up to it or immediately following. A comparison on the peak day (July 3, 2013) is provided in Figure 3-6 showing the hourly profile of the utility demand, Maydestone's total building demand and the PV generation. The SMUD peak period is shown on the chart for reference and is the light yellow shaded area. The Maydestone demand peaks two hours later than the system peak which is typical for residential customer accounts. An additional chart (Figure 3-7) for the peak demand day shows the hourly profiles of the PV generation, power exported back to the grid and the energy the house meter uses from the grid. Note that during the last hour of the peak period the PV is not producing enough power to send any back to the grid.

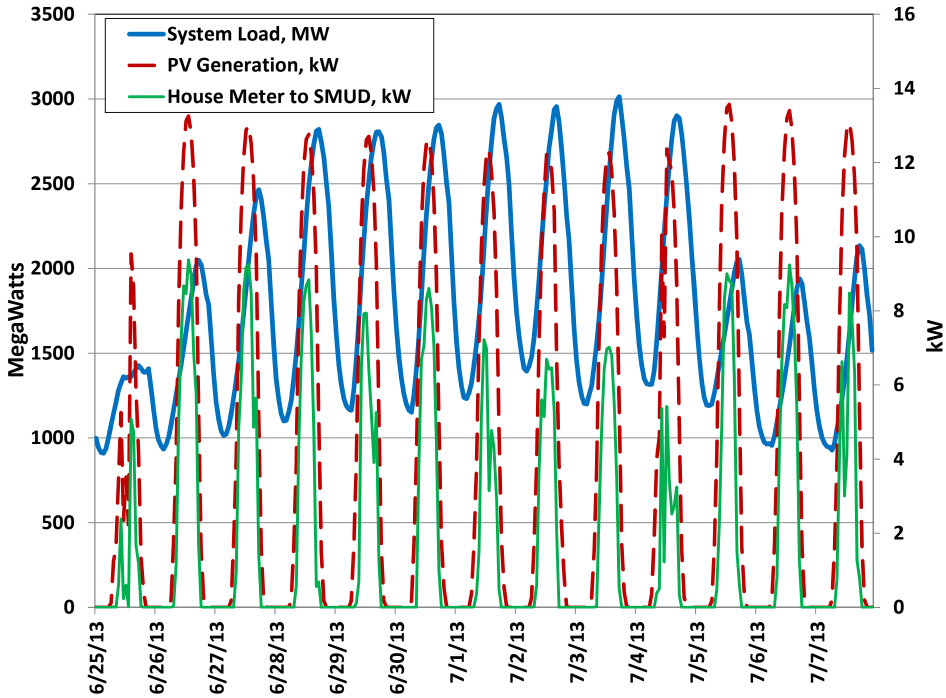

Figure 3-5 Heat Storm Loads, 2013

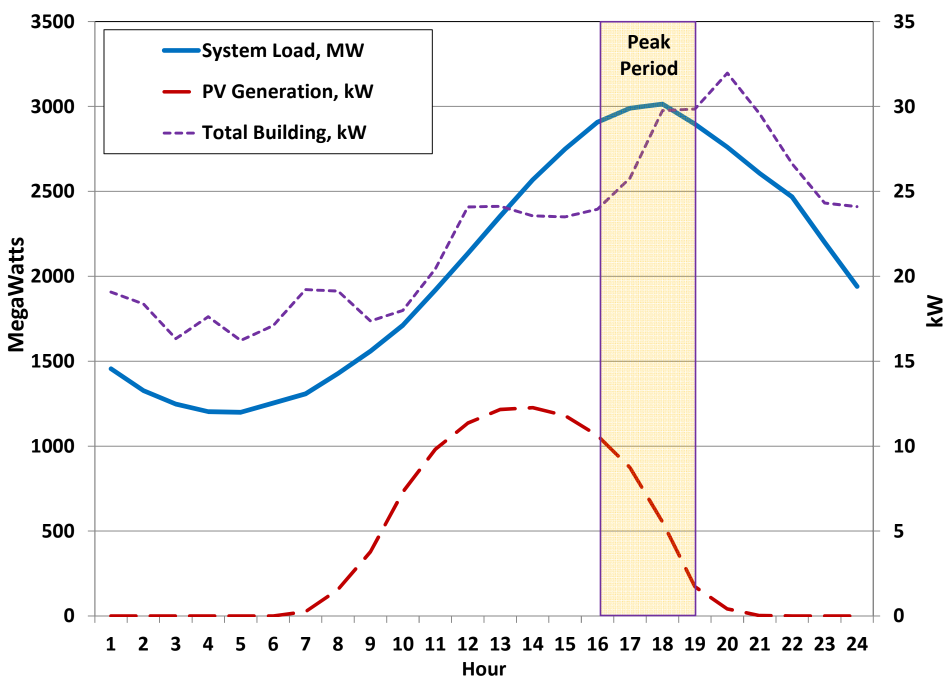

Figure 3-6 Peak Summer Day (July 3, 2013) Total Building and PV Generation Profiles

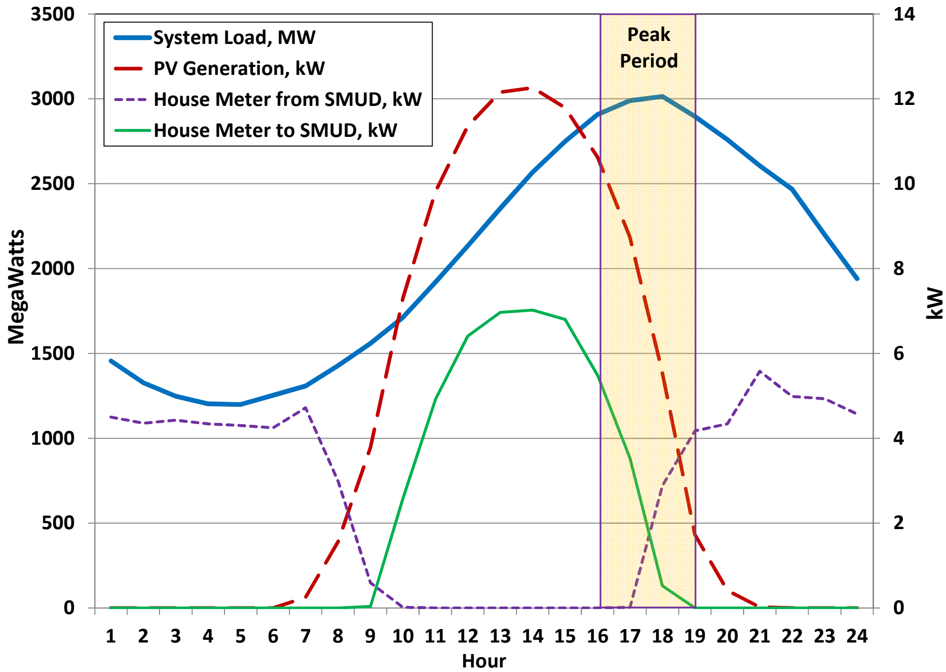

Figure 3-7 Peak Summer Day (July 3, 2013) PV Generation and House Meter Profiles

4. Mini-Split Heat Pump Evaluation

One objective of this study was to evaluate the performance of ductless mini-split systems installed in the retrofitted apartments. ADM monitored the loads on, and electrical energy used by, (4) representative heat-pump systems. The data collected on-site was compiled and analyzed using R (version 3.0.0) and used to quantify in-situ system performance. Performance metrics considered in this analysis included an *effective* Seasonal Energy Efficiency Ratio[2], system electrical power vs. outside air temperature, and system evaporator load vs. outside air temperature.

This section discusses our analysis of the ductless mini-split heat pumps and compares the monitored system loads against those predicted by the the EnergyPro simulation.

Data Validation

Data from the various loggers were merged into a single dataset with care taken to ensure that they were matched on the observation timestamps. Once compiled, the data were reviewed for consistency and validated before used in the analysis. Detailed descriptions of the data validation process are provided in Appendix B. Through the data validation process ADM found two notable items which limited the applicability of some data.

ADM noticed that the mini-split system in apartment #3 exhibited unusually short cycling times coupled with very low fan usage. While the compressor and indoor fan were constantly running, very little heat was removed from the room. As expected (and this will be shown later in this section) this resulted in very poor performance of the heat pump system. Furthermore the monitored heating and cooling loads for the unit are likely underestimated by the aberrant behavior of this HP. Thus, while the data for apartment #3 were analyzed (and the results presented later in this section), these data were not included in the final reported in-situ equipment performance and energy impact estimates. It is recommended that this unit be serviced to improve its operating efficiency.

ADM noticed two distinct behaviors when reviewing the supply air temperature data in apartment #4. ADM concluded that the temperature data following the December 19, 2012 download for apartment #4 could not be used.

Apartment Data Exploration and Trends

Several calculated fields were added to the monitored data in order to estimate the air-side system coil load and mini-split equipment efficiency. Data used in these fields (listed in Table 4-1) was limited to only that which was validated for each individual apartment.

[2] The energy efficiency ratio calculated in this analysis divided the sum total evaporator load over the monitoring period (effectively 1 year) by the sum total electrical energy used by the system over the same time period. This is referred to as an *effective* SEER value as it was not measured at AHRI conditions.

Table 4-1 List of Calculated Fields

Field Name	Description	Units
dT	Change in temperature across the indoor coil	^{o}F
dH	Change in enthalpy across the indoor coil (estimated)	BTU/lb
CFM	The flow rate of air across the coil (estimated)	CFM
LOAD	The quantity of heat being removed (or added) by the coil	BTU/h
TONS	The quantity of heat being removed (or added) by the coil	Tons
EFF	Monitored efficiency of the mini-split system	kW/Ton

The data were then aggregated from two minute intervals to hourly and monthly intervals, and also into bins of outside temperature. According to the objectives of this study, two specific relationships are of most interest: Coil Load (kBTUh) vs. Outside Air Temperature, and Average System Power (kW) vs. Outside Air Temperature. Figure 4-1 and Figure 4-2 summarize these two trends across each of the sampled apartments. It is interesting to note that for each of the apartments the inside load data intersects with the x-axis at the same outdoor air temperature as the power data. This is significant since the two data sets were generated from separate sources and yet corroborate on the heating/cooling balance point for each of the apartments.

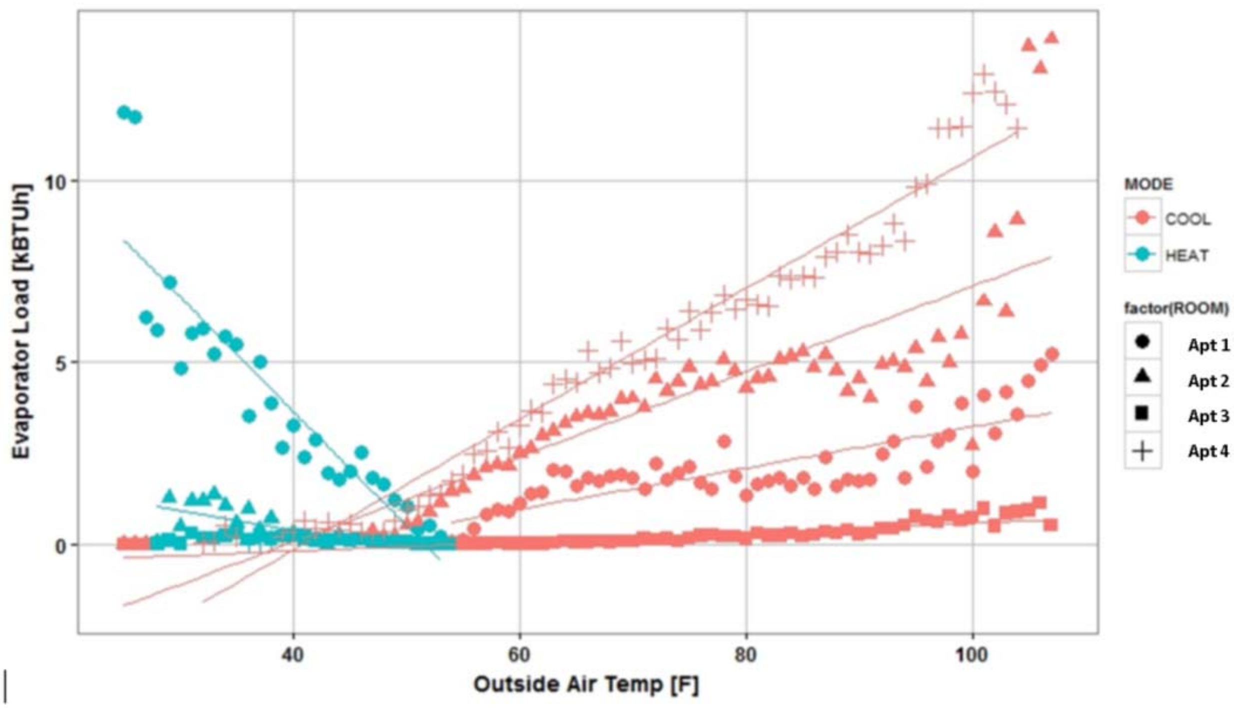

Figure 4-1 Comparison of Inside Coil Load Data across Apartments

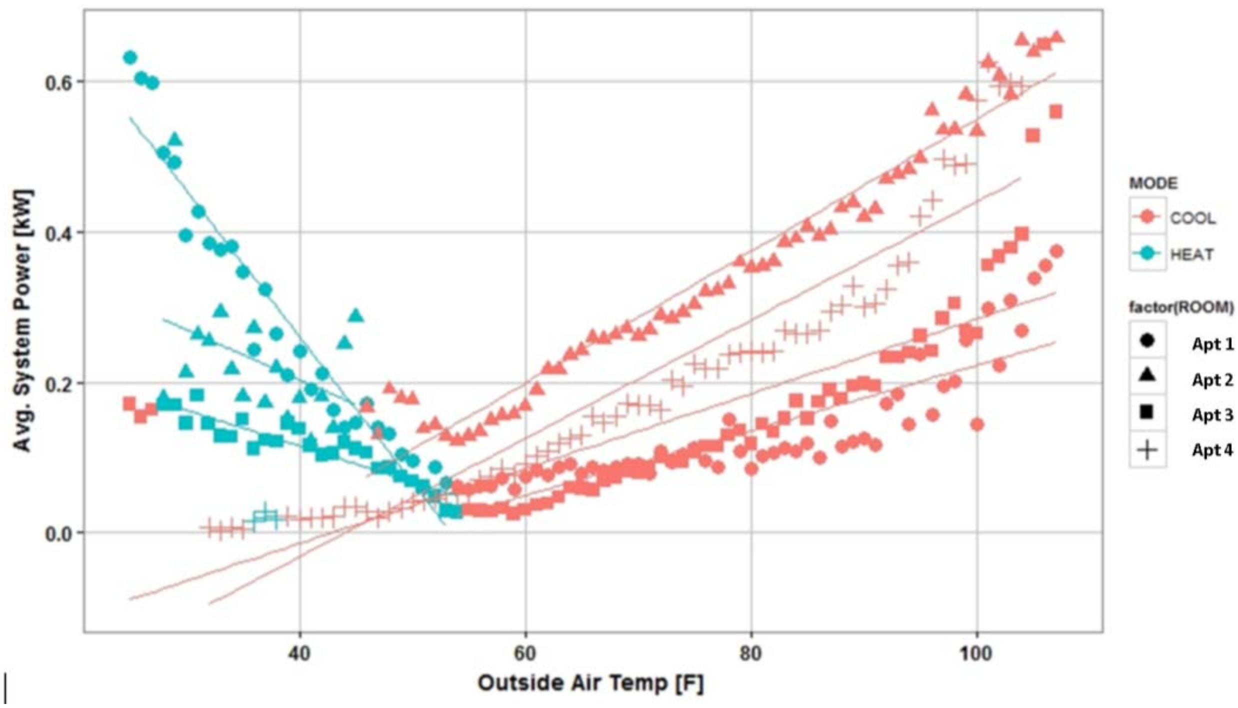

Figure 4-2 Comparison of Mini-Split Heat Pump Power Data across Apartments

While the heat pump power data is relatively consistent between each of the apartments the load data shows more variances. Most notably apartment #3 demonstrated extremely low monitored heating and cooling loads. As discussed earlier in this section, this unit displayed significant short cycling and erratic behavior in the time series data indicating that the unit may not have been operating as intended. This conclusion is further supported by the low monitored coil loads and the unrealistically low calculated efficiencies presented further into this chapter in Table 4-2.

Another point of interest in the load and power data was how high the observed cooling loads were in apartment #4 compared to the others (Apartment #4 is the largest in square footage and is on the top floor south side). This can be seen by the very low balance point (around 45 to 50 degrees) and the scarce observations of that system in heating mode. While a significant amount of winter data were removed for this apartment due to concerns over calibration bias in the temperature data, the trends as seen in the power data continued throughout all of the data for apartment #4.

Comparing Against Simulated Results

A simulation of the Maydestone retrofit was developed by Red Tape Express and provided to ADM at the beginning of this study. ADM compared the simulated cooling and heating energy use to the monitored use and noted that the two matched relatively well. In Figure 4-3 it can be seen that the heating loads show significant agreement between the simulation and the monitored data while there is some divergence in the cooling loads. The monitored data indicates higher cooling loads below approximately 90 ºF and approximately equivalent loads above that temperature. While both data-sets show a marked increase in the slope at approximately 90 ºF, the simulation predicts this shift to occur sooner (at a lower temperature). While some of this is due to differences between the simulated and observed weather (discussed below), it is likely that one or more of the following are occurring as well:

1. The actual building is not as sensitive to ambient conditions as predicted by the simulation.
2. Uncertainty is introduced because the sample of monitored rooms does not fully represent the whole building.
3. The heat pump efficiency is less sensitive to ambient condition than predicted by the simulation.

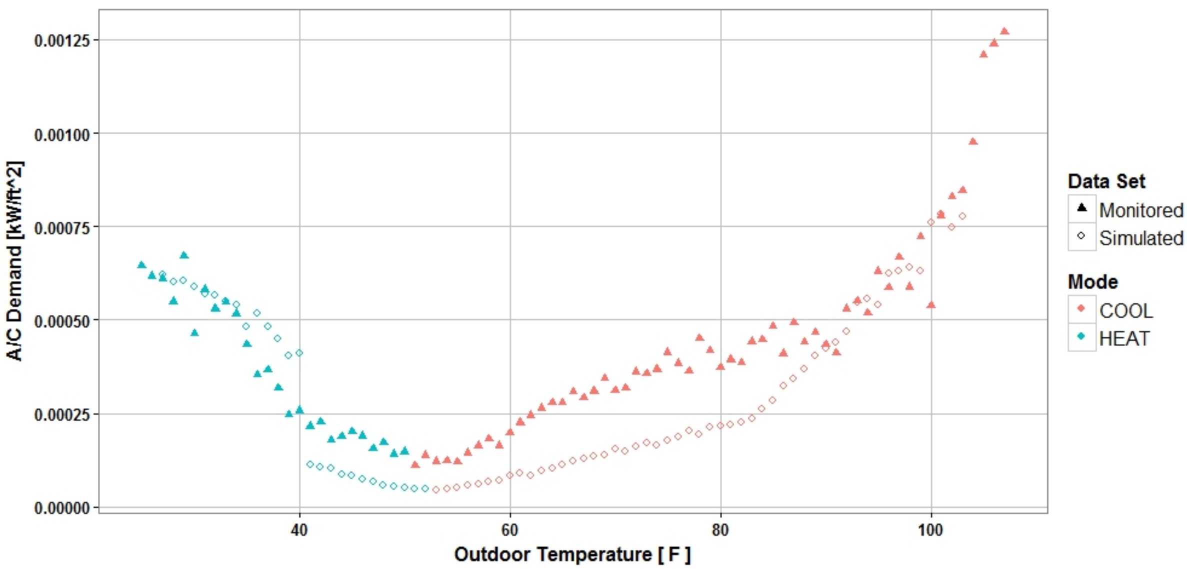

Figure 4-3 Simulated vs. Monitored Heat Pump Power per Square Foot of Conditioned Floor Area as a Function of Outdoor Air Temperature

Since the distribution of outdoor temperatures differed between the monitored time period and the weather file used in the simulation, some divergence is expected. The average outdoor temperature seen in the monitored data is slightly higher than that in the simulation weather data. This is illustrated in Figure 4-4.

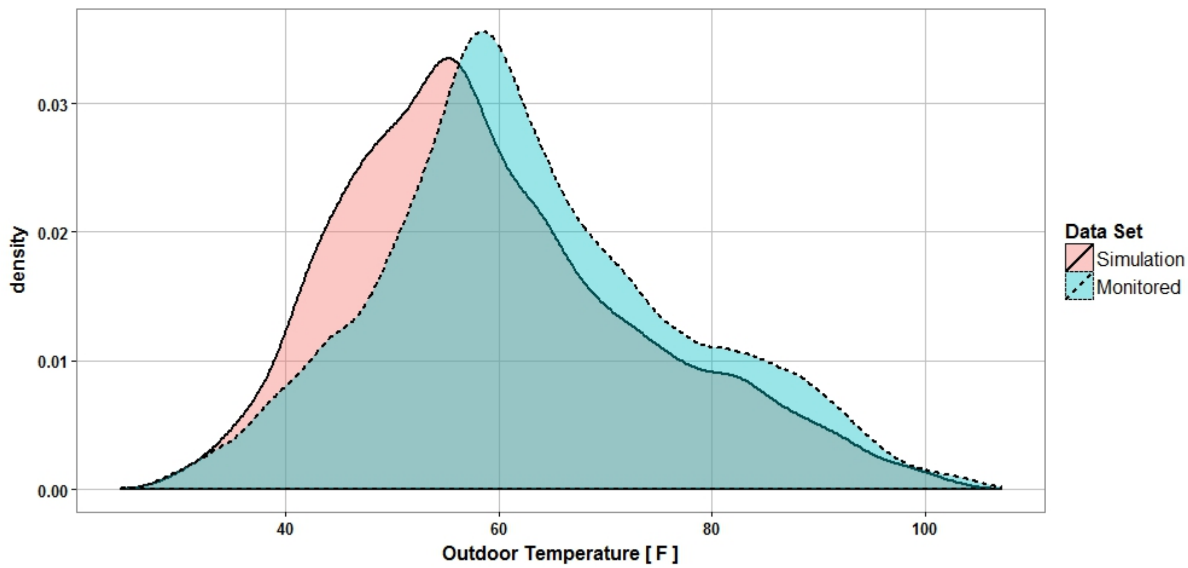

Figure 4-4 Comparison of Weather Data Outside Air Temperature Distributions

In Situ Efficiency Heat Pump Efficiency

Table 4-2 lists the calculated in-situ performance for each mini-split system in this study. Note that the in-situ performances are not directly comparable to manufacturers' ratings as the monitored systems were not operating at AHRI testing conditions. However; the measured performance can be interpreted as an *effective* SEER/HSPF since they incorporate data collected over the entire cooling and heating seasons respectively.[3] As discussed earlier in this Section, the efficiencies calculated for apartment 3 are unrealistically low due to operational issues observed in the data (e.g. the unit was being operated outside of its intended use or there was a malfunction in the unit). Thus, while it is presented here in Table 4-2, its value was not included in the average. The in-situ equipment performance largely lined up with the SEER and HSPF values as reported by the manufacturer though the unit serving apartment 4 demonstrated an unexpectedly high efficiency in cooling mode.

Table 4-2 Monitored Mini-Split Equipment Performance by Apartment

Apartment #	Monitored $SEER_{Effective}$	Monitored $HSPF_{Effective}$	Manufacturer SEER	Manufacturer HSPF
1	17.9	11.1	23	11
2	20.8	8.5	23	11
3	1.7	0.6	23	11
4	31.7	13.6	21	11
Average[4]	23.5	11	22.5	11

[3] The *effective* energy efficiency ratio calculated in this analysis divided the sum total evaporator load over the monitoring period (effectively 1 year) by the sum total electrical energy used by the system over the same time period. This is referred to as an *effective* SEER/HSPF value as it was not measured at AHRI conditions.
[4] Average monitored efficiency does not include apartment 3.

While we observed differences in magnitude across heat pump efficiencies Figure 4-5 demonstrates that each showed similar responses to outdoor air temperature.

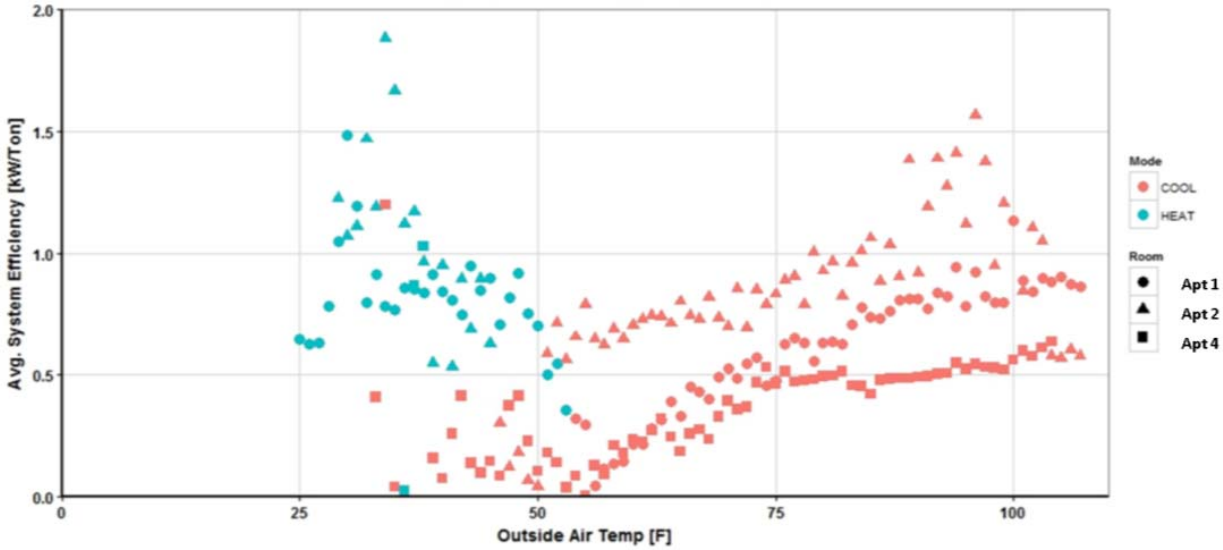

Figure 4-5 Effect of Outdoor Temperature on Mini-Split Heat Pump Efficiency

Estimated Energy Impacts

ADM normalized the monitored power data for apartments 1, 2, and 4 using the conditioned area of each apartment. The normalized data were averaged into temperature bins in order to observe the overall monitored response of heat pump energy to outdoor air temperature. This relationship is shown in Figure 4-6. The data were split to represent "heating" and "cooling" modes of operation and fitted using linear regression.

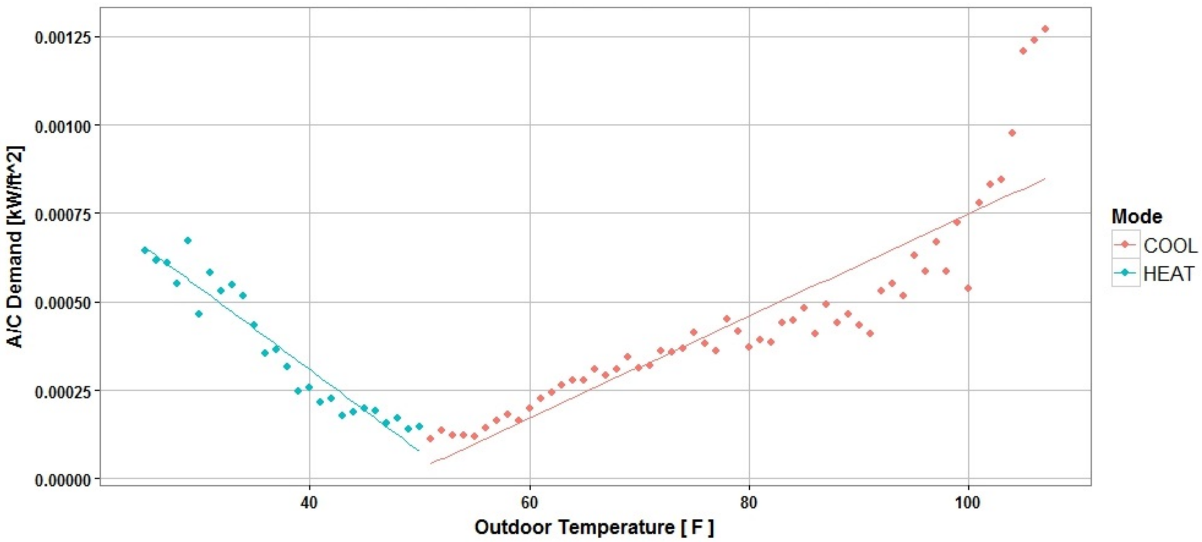

Figure 4-6 Line Fits Used to Weather Normalize Monitored Data and Extrapolate to TMY3

The data indicate an overall balance point of approximately 51 ºF and roughly equivalent slopes in heating and cooling mode. The fits (which are shown in Figure 4-6) and summarized in Table 4-3 were applied to TMY3 data and used to extrapolate the annual "monitored" heat pump energy use. The baseline energy use was estimated by multiplying by the ratio of monitored to baseline unit efficiency. Baseline unit efficiency was determined using the 2010 California Appliance Efficiency Regulations minimum efficiency standards for "Other air-cooled heat pumps." The baseline and as built efficiencies used in the energy savings estimates are shown in Table 4-4.

Table 4-3 Summary of Line Fit Parameters

Fit Parameter	Cooling Mode	Heating Mode
Slope [kW/(ft^2*F)]	-6.95E-04	1.23E-03
Intercept [kW/ft^2]	1.44E-05	-2.31E-05
R^2	0.79	0.92

Table 4-4 Summary of Efficiency Values Used in Savings Estimate Calculations

Case	SEER	HSPF
Baseline	13	7.9
As Built	22.5	11
As Measured	23.5	11

The monthly energy use predicted by TMY3 weather data and the line fits is illustrated in Figure 4-7 along with the monthly estimated energy savings. The extrapolated energy impacts are illustrated in Figure 4-7 and Figure 4-8. Both the simulations and monitored data indicate that the cooling loads for the Maydestone building are much larger than its heating loads. This can be seen by the dramatic increase in system electrical demand between May and October in Figure 4-7.

Table ***4-5*** summarizes the annual energy and peak demand savings estimates for the high efficiency heat pumps.

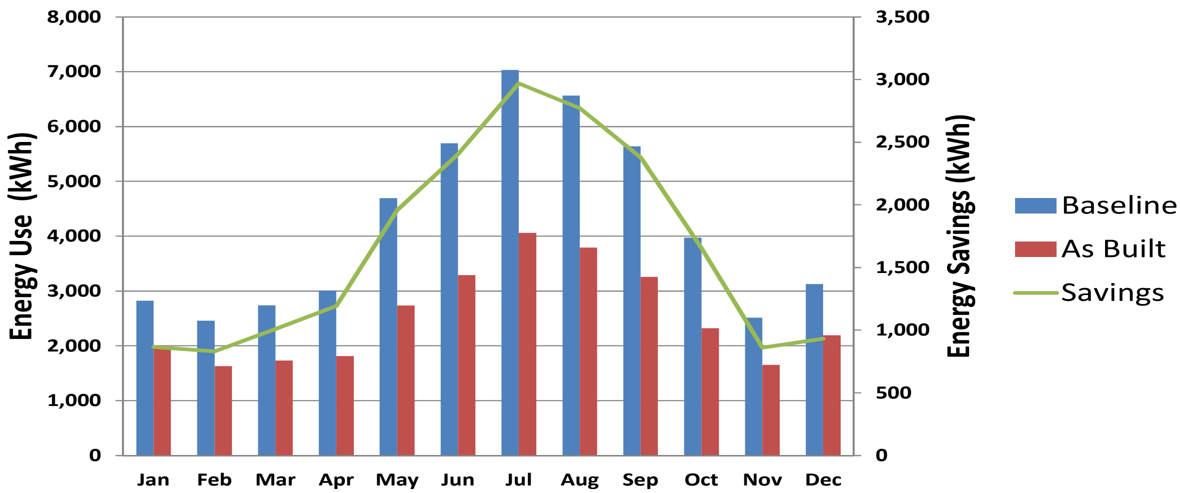

Figure 4-7 Comparison of Pre and Post Estimated Energy Use for High Efficiency Heat Pumps

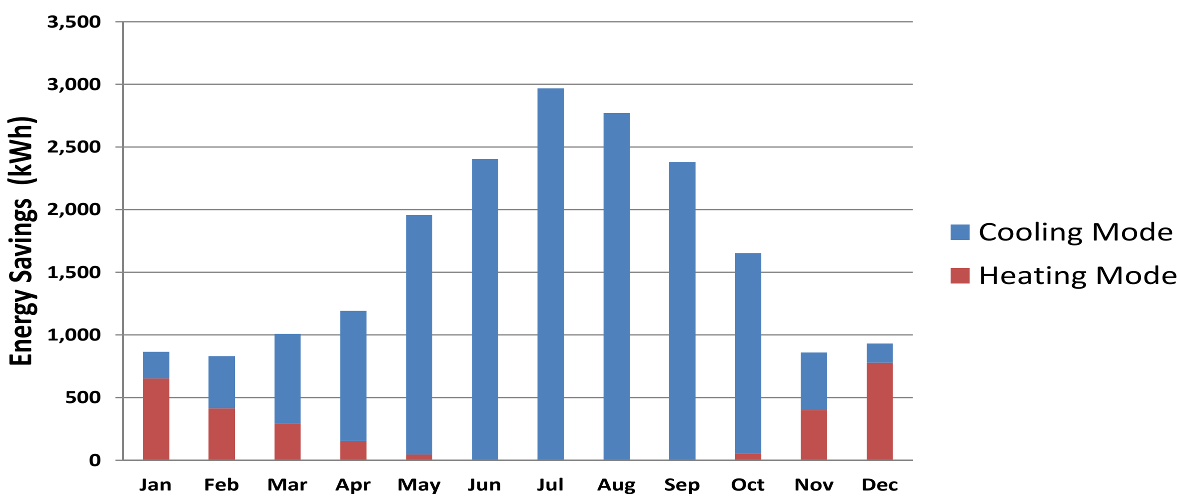

Figure 4-8 Estimated Monthly Energy Impacts for Heat Pumps in Heating and Cooling Modes

Table 4-5 Summary of Energy Savings and Peak Demand Reduction Estimates for Heat Pumps

Annual Energy Savings	24,709 kWh
Peak Demand Reduction	13.6 kW

Heat Pump versus Total Apartment Electrical Energy

The SMUD Smart meter data were used to show a comparison of the four sampled apartment's energy use versus the monitored heat pump energy use (see Table 4-6). The annual period presented runs from June 1, 2012 to May 31, 2013, except for apartment #4 where the annual period presented runs April 1, 2012 to March 31, 2013 because of vacancy in April 2013. Apartment #4 is the largest apartment (most floor area) and also has the highest internal energy use not attributable to the heat pump. The usage patterns are very dependent on the tenants occupying the apartment. Additional data from SMUD shows that the average annual energy use across all 32 apartments for the period from October 21, 2012 to October 20, 2013 was 3,044 kWh. This is close to the average of the four units (2,930 kWh) which were monitored in depth indicating they were typical for this building. The heat pumps account for almost 30% of the apartments energy use. Monthly total and heat pump energy use charts by apartment are presented in the Appendix C.

Table 4-6 Total and Heat Pump Annual Energy Use by Apartment

	Apt 1	Apt 2	Apt 3	Apt 4	Average	Modeled (per Apt)[5]
Annual Apt. Meter Load, kWh	2,707	3,142	1,694	4,176	2,930	2,885
Annual Apt. Meter Load, kWh/ ft^2	5.52	8.49	5.61	6.03	6.41	6.37
Annual HP Energy Use, kWh	942	1,022	462	1,028	864	374
Annual HP Energy Use, kWh/ft^2	1.92	2.76	1.53	1.48	1.93	.82
% HP of Total Apt. Load	34.8%	32.5%	27.3%	24.6%	29.5%	13%
Annual Heating Energy Use, kWh	220	239	108	241	202	94
Annual Cooling Energy Use, kWh	722	783	354	787	661	393
Other Electrical Load, kWh	1,765	2,120	1,232	3,148	2,066	2,511
Apartment Floor Area (ft^2)	490	370	302	693	464	453[6]
Rated Heat Pump Cooling (tons)	0.75	0.75	0.75	1.2	-	-

The apartment and heat pump average hourly demands are tabulated in Table 4-7 for two conditions. The first is the heat storm of 2013, which the following weekdays (WD) were included (June 28, July, 1, 2, and 3). Demands were averaged over the SMUD peak period time from 4:00 PM to 7:00 PM. During the heat storm, the heat pumps used a significant portion of the electricity used in each apartment and ranged from approximately 64% to 89%. The second condition is the SMUD peak period for weekdays during the entire summer (June 1 through September 30). During the average summer weekday peak period the heat pumps use from approximately 39% to 65% of the energy used in the apartment.

[5] Note that the numbers listed for the Modeled per apartment heat pump energy use reflect "normalized" weather data and not the actual weather during the monitoring period.
[6] Total apartment area = 14,494 square feet.

Table 4-7 Total and Heat Pump Average Hourly Demands by Apartment

Conditions	Parameter	Apt 1	Apt 2	Apt 3	Apt 4
2013 Heat Storm Demand SMUD WD Peak (4-7 PM)	**Apt. Demand, kW**	**0.768**	**0.776**	**0.549**	**0.881**
	Heat Pump Demand, kW	**0.489**	**0.627**	**0.441**	**0.780**
	%HP of Apt. Total	**63.7%**	**80.8%**	**80.4%**	**88.6%**
Ave. 2013 Summer Demand in SMUD WD Peak (4-7 PM)	**Apt. Demand, kW**	**0.584**	**0.600**	**0.345**	**0.337**
	Heat Pump Demand, kW	**0.237**	**0.391**	**0.214**	**0.133**
	%HP of Apt. Total	**40.6%**	**65.2%**	**62.2%**	**39.4%**

Temperatures in Apartments

The temperatures in the four monitored apartments were analyzed to determine how well the heat pumps maintained the temperature. The return air temperature sensor was used as a proxy for room temperature since it is located inside the room, not in a duct, but is generally above head height. There is a lot of variation in the temperature, which can happen if the room is unoccupied and the HP is turned off. No data is available on the thermostat set points or occupancy of the apartments to determine if the temperature analyzed represent conditions the occupants intended to maintain the space at a comfortable level.

The values in Table 4-8 show that the temperatures in most of the rooms were not stable. In the summer when the HP was running the average temperatures ranged from 72 to 80 with a standard deviation of 2 to 3. Apt 4 was the least stable with the temperature generally around 72. As mentioned previously apartment #3 had problems with the HP and the temperatures for that room reflect a different operation than the other rooms.

Table 4-8 Temperatures (ºF) in Apartments for Various Conditions

Temperature Condition	Apt 1	Apt 2	Apt 3	Apt 4	Modeled	Average[7]
Average Summer	75	77	80	72	75	76
Max. Summer	83	86	92	80	75	85
Min. Summer	67	71	72	67	75	69
Std. Dev. Summer	2	2	3	3	n/a	3
Average Summer, when HP on	75	76	79	72	75	76
Max. Summer, when HP on	82	85	86	80	75	83
Min. Summer, when HP on	67	71	72	67	75	69
Std. Dev. Summer, when HP on	2	2	2	3	n/a	2
Average Winter	73	72	76	70	70	73
Max. Winter	93	87	87	79	70	87
Min. Winter	61	61	64	62	70	62
Std. Dev. Winter	6	4	3	2	n/a	4
Average Winter, when HP on	78	72	78	70	70	75
Max. Winter, when HP on	93	87	87	79	70	87
Min. Winter, when HP on	61	63	64	66	70	64
Std. Dev. Winter, when HP on	7	4	3	2	n/a	4

[7] Note that the Average includes only measured apartment temperatures and does not include the Modeled temperatures.

5. Conclusions

The objectives of this study were to:

1. Electrical Energy Use
    a. What was the simulated annual energy use and electrical peak demand of this building prior to DER?
    b. What is the simulated annual energy use and peak demand after DER?
    c. What is the measured annual energy use and peak demand?

2. Space Conditioning System
    d. What is the measured performance of HPs under test weather conditions?
    e. How does this compare to simulated performance under similar weather conditions?
    f. How does this compare to published SEER and HSPF performance data?
    g. How effectively does space conditioning system maintain comfortable and/or consistent temperatures?
    h. How effectively does the air handling unit maintain consistent temperatures with and without the HP?

In addition, the following are addressed:

1. Measure the in-situ efficiency of a sample of ductless mini-split heat pumps,
2. Estimate the energy savings due to the high efficiency ductless mini-split heat pumps,
3. Leverage monitoring data to discern how performance of future projects can be improved.

This section presents the conclusions drawn from the findings discussed in the previous sections as they relate to the objectives. The whole building energy use and demand as simulated and metered is provided in Table 5-1.

Table 5-1 Energy Use and Peak Demand Estimates for DER Whole Building

	Annual Energy Use	Peak Demand
Pre DER Simulation	201,119 kWh	62 kW
Post DER Simulation	115,182 kWh	30.5 kW
Metered (Actual Weather)	135,252 kWh	29.1 kW
Metered (Normalized Weather)	134,585 kWh	23 kW
Ex Ante Savings	85,937 kWh	31.5 kW
Ex Post Savings	71,461 kWh	39.2 kW

The values in Table 5-2 show that the average measured temperatures were relatively stable. In the summer when the HP was running the average temperatures ranged from 72 °F to 79 °F with a standard deviation of 2 °F to 3 °F. The measured apartment temperature when the heat pump was on and in cooling mode was almost the same as the modeled cooling set point temperature. This does not explain why the HP cooling energy use is much higher than the modeled cooling energy use. In contrast, the measured apartment temperature when the heat pump was in heating mode was 5 °F higher than the modeled heating set point temperature, which does support the under prediction of HP heating energy use by the model.

Table 5-2 Temperatures (ºF) in Apartments for Various Conditions

Temperature Condition	Modeled Average (°F)	Measured Average (°F)
Average Summer, when HP on	**75**	**76**
Std. Dev. Summer, when HP on	**-**	**2**
Average Winter, when HP on	**70**	**75**
Std. Dev. Winter, when HP on	**-**	**4**

Recommendations for Future Studies

Projects like DER have many sources of energy savings. Measurements to segregate the savings into each measure application can be invasive and costly. If the overall impact of the project is of most importance then savings analysis using billing meters is the most cost effective approach when a baseline exists. If no baseline exists then an energy simulation normalizing the post period to actual billing data is appropriate. If funding is available segregation of end use loads such as plugs and lighting in multi-family housing could be used to compare against modeled and Title 24 energy assumptions. These type of end use loads would typically be input to models by power density normalized per square foot.

ADM found that the in-situ performance of the ductless mini-split systems were in line with the manufacturer's claims. There generally will be differences between manufacturer's lab ratings of energy efficient equipment versus field test measurements. Some can be attributed to differences in conditions, differences in operation, or proper installation and commissioning. Opportunities to minimize any of these differences in the study will provide better study results.

It is also suggested that a comparison of heating and cooling temperature set point assumptions for Title 24 as modeled values versus average values measured in actual multi-family housing units be made to inform any observed load differences.

In this project, the detailed analysis that was conducted indicates that one of the four units was not performing as expected. If preliminary detailed analysis of the data had been conducted part way through the project then the issue could have been addressed. Although generally this level of equipment inefficiency results in customer complaints which prompts a service call to fix the problem. For long term projects it is suggested to conduct detailed analysis before the mid -term point of data collection (in addition to at the end of data collection). This could save the project from having "good" data but for a "bad" or poorly performing system.

It is also suggested that additional studies obtain end use data for more multi-family housing particularly for new construction to inform Title 24 code model assumptions.

6. Appendix A: Monitoring Instrumentation

Monitoring Instrumentation

Stand-alone Onset HOBO® data loggers were installed in each of the four sampled apartments to monitor supply and return air temperatures and return air humidity listed in Table 2-1 for the space conditioning system efficiency objective. The supply air temperature sensor was a type-T thermocouple attached to the front of the supply grill and recorded on 2-minute intervals. Regular visits to the apartment building were conducted to download logged data. Outdoor air temperature and relative humidity were monitored using HOBO® Outdoor Pro v2 temperature and humidity loggers mounted in a protected area on the roof of the building. Outdoor conditions were recorded on 10-minute intervals. Two 8-channel Enernet K-20 power recorders were installed on the roof to monitor the total compressor/outdoor fan/indoor fan power and the air handler power for the four sampled mini-split system heat pumps that match up with the apartment units being monitored. The K-20 can monitor electric energy, analog signals and digital pulses. This multi-channel meter recorder is used to monitor true rms kW power of electric loads. Two K-20 recorders were used to extend the memory storage period to 45 days for the 2-minute integrated power measurements. Hourly weather data were downloaded from a local weather station covering the duration of the monitoring period. One-time airflow measurements were also taken for each of the sampled indoor fan-units. Measurements were taken in each of the (4) fan modes; quiet, low, medium, and high.

We relied on SMUD installed SMART meters in the Maydestone apartment building to measure and record electrical energy use for each apartment and the common areas (house meter). SMUD provided hourly average kW (kWh) data for the four sampled apartment units, the house meter, and the photovoltaic (PV) meter.

Monitoring Equipment Accuracies

HOBO® loggers from Onset Computer Corp. were used. These are small battery operated loggers. HOBO® U12-013 temperature and relative humidity loggers with a range of -4 ºF to 158 ºF and from 5% to 95% RH with accuracies of ± 0.63 ºF at 77 ºF (Resolution=0.05 ºF) and ± 2.5% RH from 10% to 90% RH were used for the return air measurements. These loggers hold 60 days of 2-minute interval snap-shot measurement data. HOBO® U12-014 thermocouple data loggers were used to monitor the supply air temperature. Type-T thermocouple with these loggers have a range of -328 ºF to 212 ºF with accuracies of ± 2.7 ºF and resolution of 0.18 ºF at 58 ºF. The outdoor HOBO®s (U23-001) have a range of -40 ºF to 158 ºF and from 0% to 100% RH with accuracies of ± 0.38 ºF (resolution = 0.04 ºF at 77 ºF) and ± 2.5% RH from 10% to 90% RH (resolution = 0.03% RH).

The K-20 logger accuracy for a power measurement is ±0.5% from 1 to 100% of full scale. Current transformer accuracy is ± 1% from 10% to 100% of full scale, ± 3% at 5% of full scale and ±5% at 2% of full scale. Split-core current transducers with 20 Amp primary ratings were used to monitor the total load of the rooftop heat pump units, while 5 Amp CTs were used to monitor the air handlers.

7. Appendix B: Heat Pump Data Validation Process

Validation process

Each time data were downloaded they were visually inspected using charts the logger software provides to confirm all data points were being collected and the data was within expected ranges. After all the data for the project was collected it was validated by overlaying time series plots of the monitored parameters. Trends in the data were reviewed for internal consistency. For example, when the compressor turns on the supply air data should begin to drop and a temperature delta established across the coil. Furthermore, one would not expect there to be much (if any) delay between the compressor engagement and the supply air temperature drop at the time steps used in this study (2 minute for supply air and power data). An example of such a plot is illustrated in Figure 7-1. In the example plot, note how the supply air temperature (TEMP.SA) data responds very closely with the compressor data (HP.POWER). The indoor supply fan (FN.PWR) in this chart is on only when the compressor is running implying the fan is in auto mode. The unit cycling is cleanly represented in both the supply and return air temperature data. Furthermore there are no apparent shifts in time between any of the graphed data series (e.g., one series advanced or delayed by an increment in time). It should be noted that the supply air, return air, and power data are all collected by separate loggers. Thus the consistency by which their data correlate generates confidence in the subsequent trends.

Data from supply and return air temperature loggers were also reviewed to test if any measurement bias was observable as this would directly impact the calculated coil loads (and therefore bias the calculated efficiencies). The presence of bias due to miscalibration of the temperature loggers was tested by graphing the monitored supply air temperatures against the monitored return air temperatures (for a given apartment) – limiting the observations to intervals in which it was expected that the two should read equivalent temperatures (for example they were limited to times when the compressor was off).

Figure 7-2 demonstrates the results of this test for apartment #2 and the significance of each plot is described in Table 7-1.

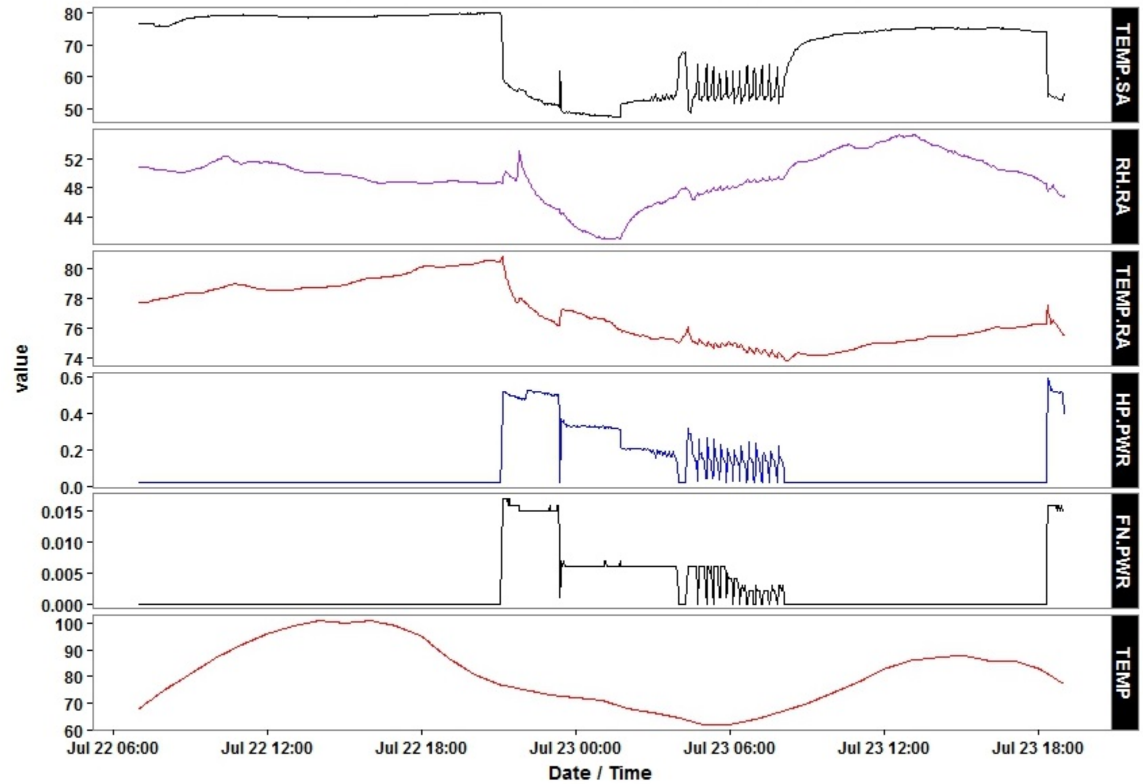

Figure 7-1 Example Time Series Plot Used for Data Validation, Apartment #1

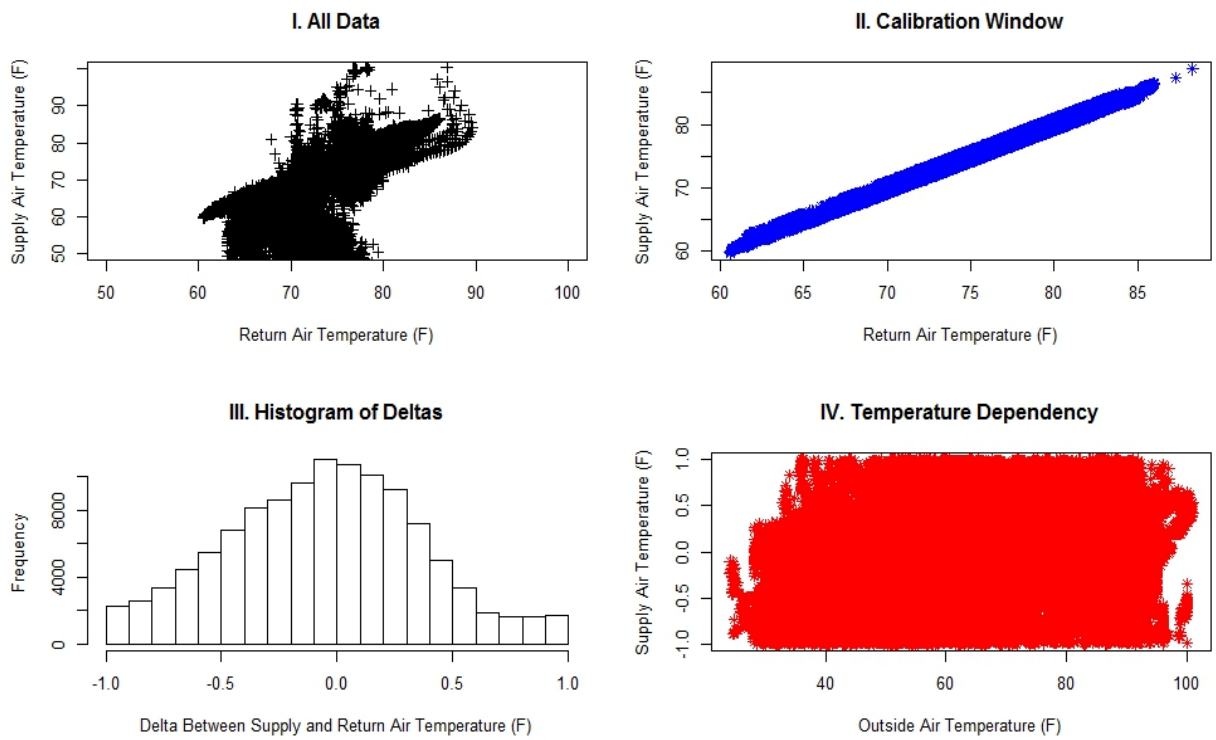

Figure 7-2 Example of Tests Used To Validate Temperature Data, Apartment #2

Table 7-1 Description of Plots in Figure 7-2

Quadrant	#	Description	Significance
Upper Left	I	Plots the entire data set when the supply air is above 50ºF independent of compressor operation. Shows overall trends and scatter in the data set.	Used to identify if multiple structures exist in the data.
Upper Right	II	Plots only the observations where the supply and return loggers "should" be reading the same thing (e.g. in a spans of time where the compressor has not run for a while and the fan on).	Graphically Illustrates error and/or bias in the air temperature data.
Lower Left	III	A histogram of the delta between the logger readings for all of the observations. Note that only a delta range of -1 ºF to +1 ºF is displayed, implying that the compressor is off for the displayed data.	Demonstrates whether or not the error observed in the temperature deltas is randomly distributed.
Lower Right	IV	Plots the delta between the loggers (for only the observations seen in plot II) against outside air temperature.	Demonstrates whether or not there is a temperature dependency on the error in the supply and return logger data. Look for no trend.

Note how in Plot II (Calibration Window) the points make a tight line that, if extended appears to intercept the y-axis near 0. It should be noted that some of the "tightness" observed in the data in Plot II is due to how the observations were filtered out. When reviewing these data we limited these observations to ones whose difference (e.g. supply temperature minus return temperature) fell within a certain range. The sensitivity of the results to different thresholds was explored in order to make sure that such a filter did not introduce its own bias. Looking at the histogram in Plot III we can see that the average "error" in the delta seen in the data for apartment #2 is normally distributed around -.05. If the threshold is increased or reduced the mean of the data remains the same due to the nature of this distribution. Thus we are confident that calibration bias is not a major concern for this particular data-set.

Validation Issues

Through the data validation process ADM found two notable items which limited the applicability of some data – though only one of which was due to "untrustworthy" data.

Equipment Operation for Apartment #3

When reviewing the time series data for apartment #3, ADM noticed that the mini-split system exhibited unusually short cycling times coupled with very low fan usage. While the data itself was internally consistent (e.g. the various parameters tracked each other according to physical first principles), and there were no calibration biases observed in the temperature logger data, the cycling behavior of the mini-split system was unusual. A sample of this time series data is shown in Figure 7-3. Throughout the entire plotted period the compressor is "short-cycling" while there is only a very short interval in which the fan is operating and even then it is at its lowest setting. Thus, while the compressor and indoor fan were constantly running, very little heat was removed from the room. As expected (and this will be shown later in this section) this resulted in very poor performance of the heat pump system. Furthermore the monitored heating and cooling loads for the unit are likely underestimated by the aberrant behavior of this HP. Thus, while the data for apartment #3 were analyzed (and the results presented later in this section), these data were not included in the final reported in-situ equipment performance and energy impact estimates. It is recommended that this unit be serviced to improve its operating efficiency.

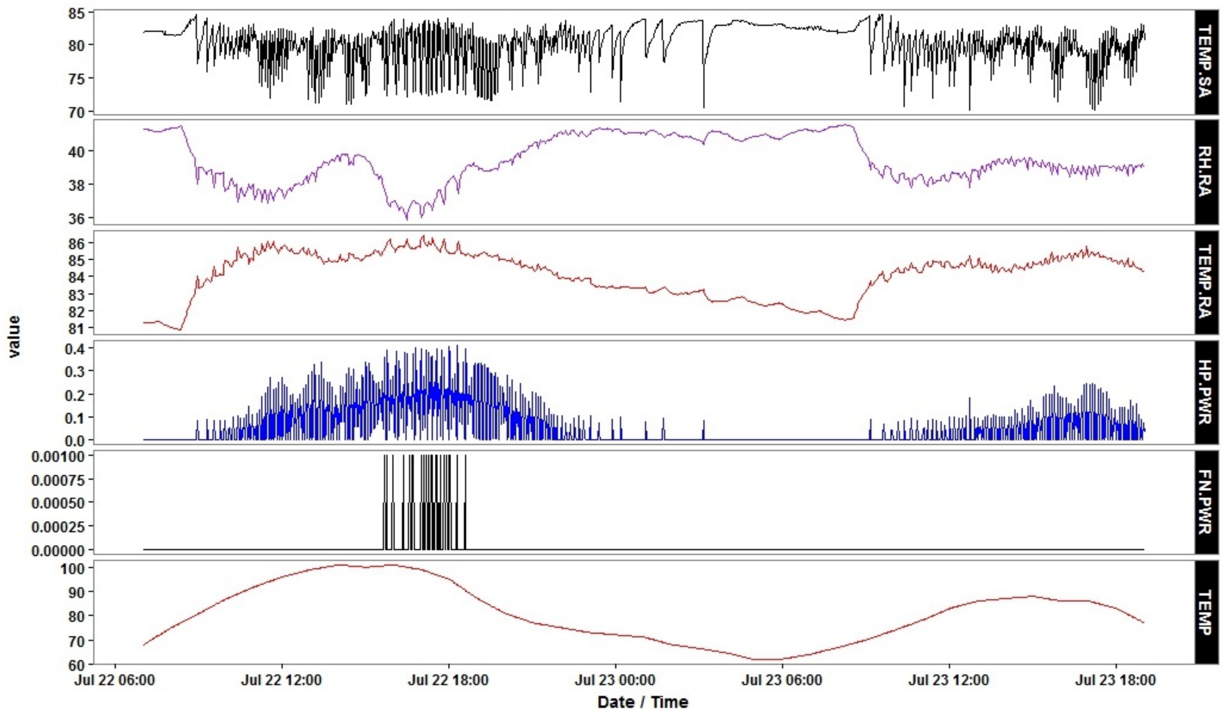

Figure 7-3 Time series Depicting Erratic Behavior of Mini-Split in Apartment #3

Calibration Bias Noted In Apartment #4

ADM noticed two distinct structures in Plot I (All Data) when reviewing the temperature data in apartment #4 (shown in Figure 7-4). In addition to the expected y = x line of matching points was a line of observations showing a y-intercept much greater than 0 and a slope whose value was less than 1. Furthermore, the line exhibited a slight curvature which indicated that there was a temperature dependence on the slope. Through further analysis ADM discovered that the points comprising this “structure” appear immediately following one of the data logger downloads during which the logger batteries were replaced. ADM concluded therefore that the temperature data following the December 19, 2012 download for apartment #4 could not be used due to significant calibration bias introduced by the battery change.[8]

[8] Note that this is the first time ADM has observed a battery replacement that impacted the logger calibration. Battery replacements were performed in the temperature loggers in the other apartments with no impact on their calibration.

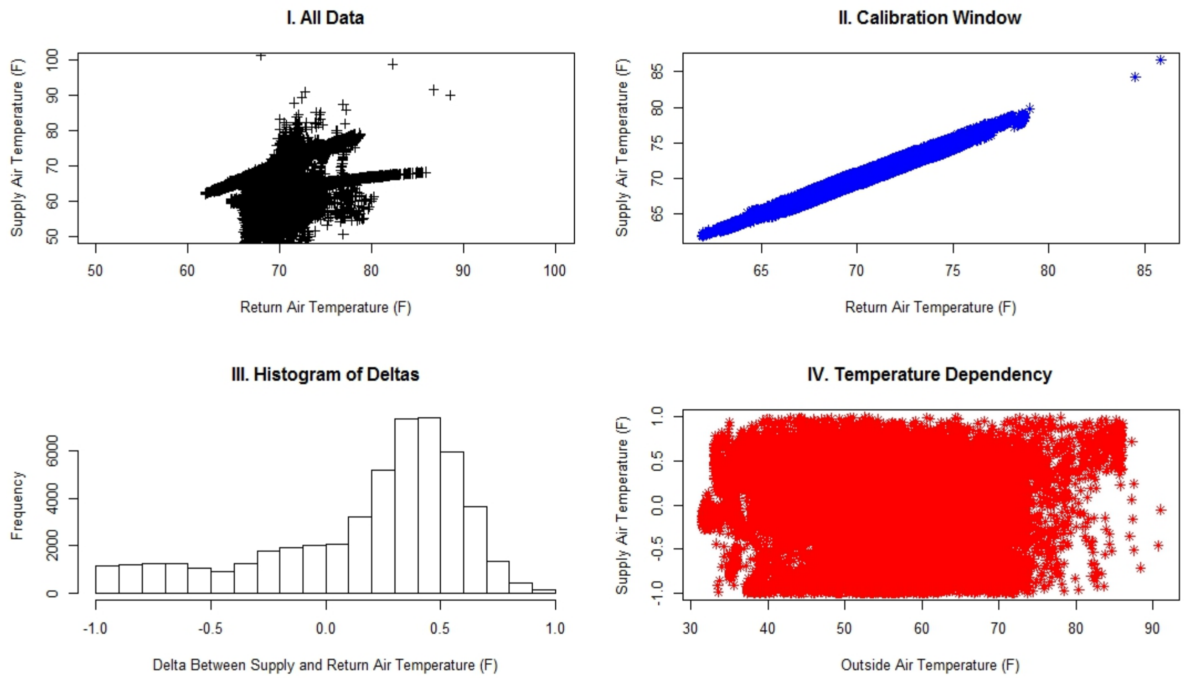

Figure 7-4 Temperature Data from Apartment #4

8. Appendix C: Additional Data Charts

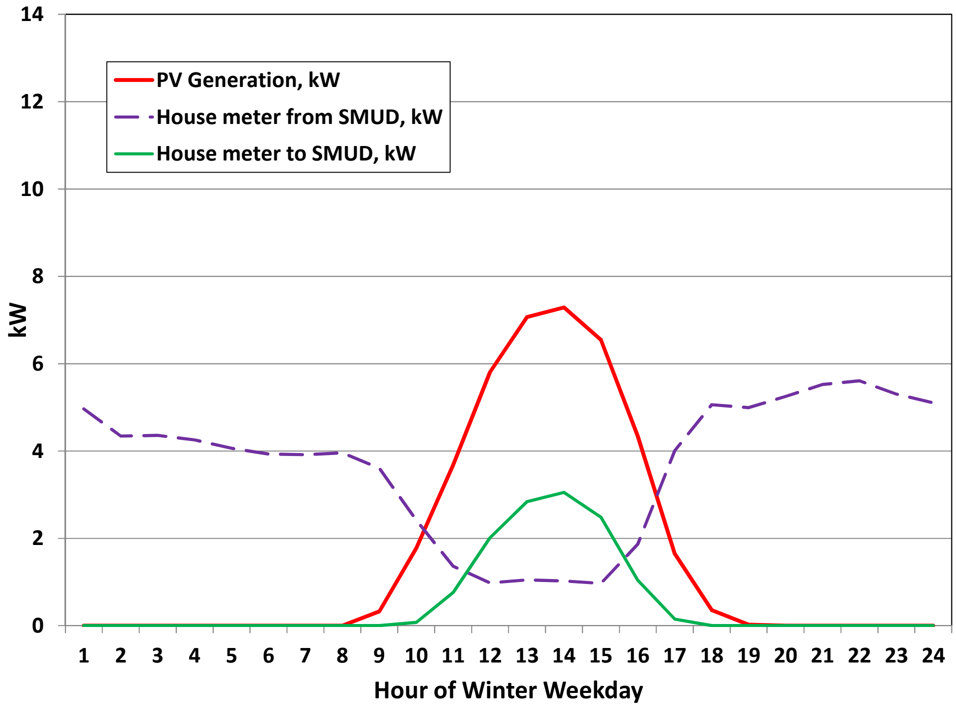

Figure 8-1 Typical Winter Day PV Profile and House Meters

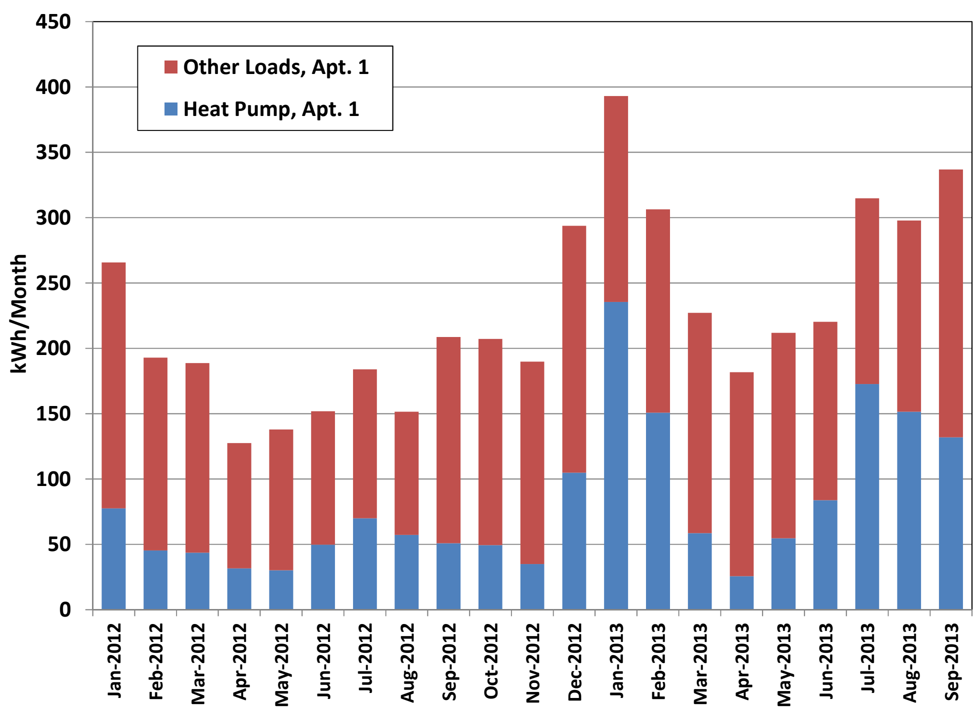

Figure 8-2 Monthly Energy Use in Apartment 1

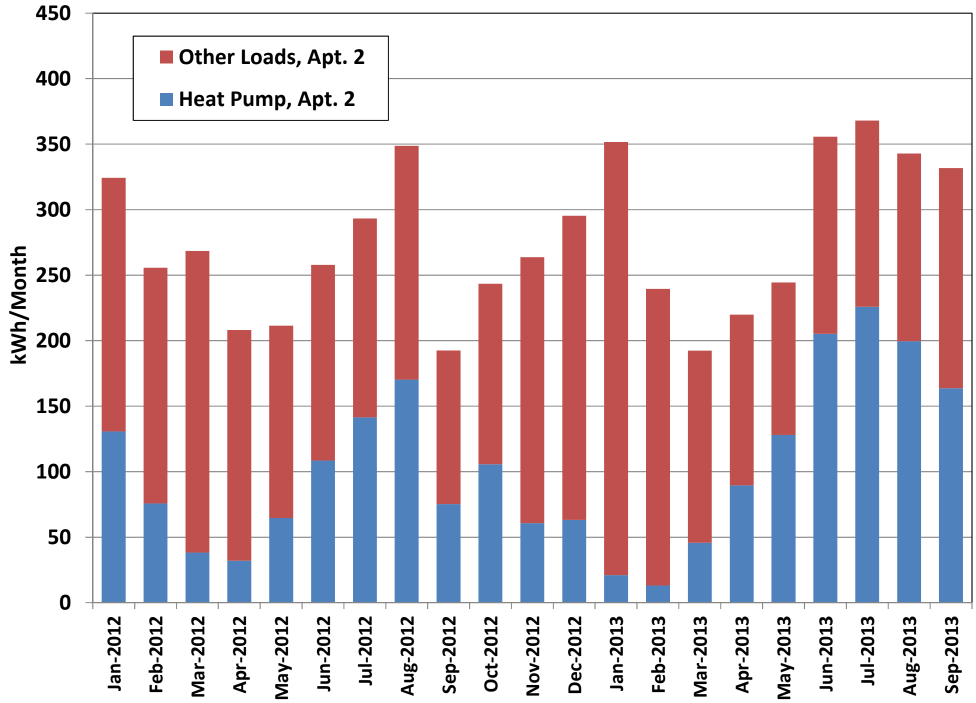

Figure 8-3 Monthly Energy Use in Apartment 2

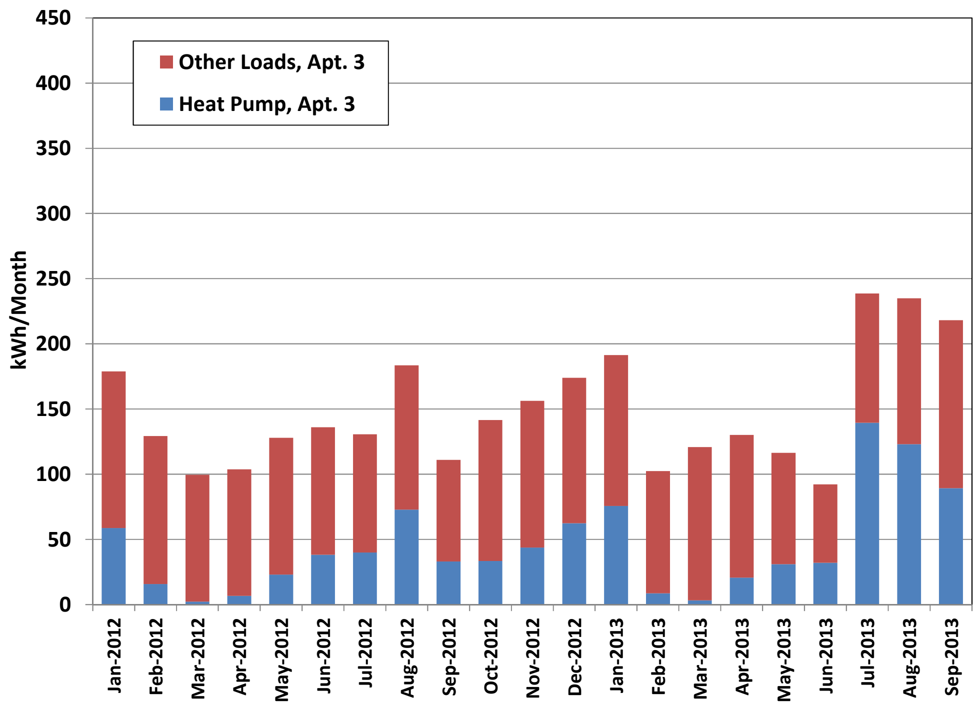

Figure 8-4 Monthly Energy Use in Apartment 3

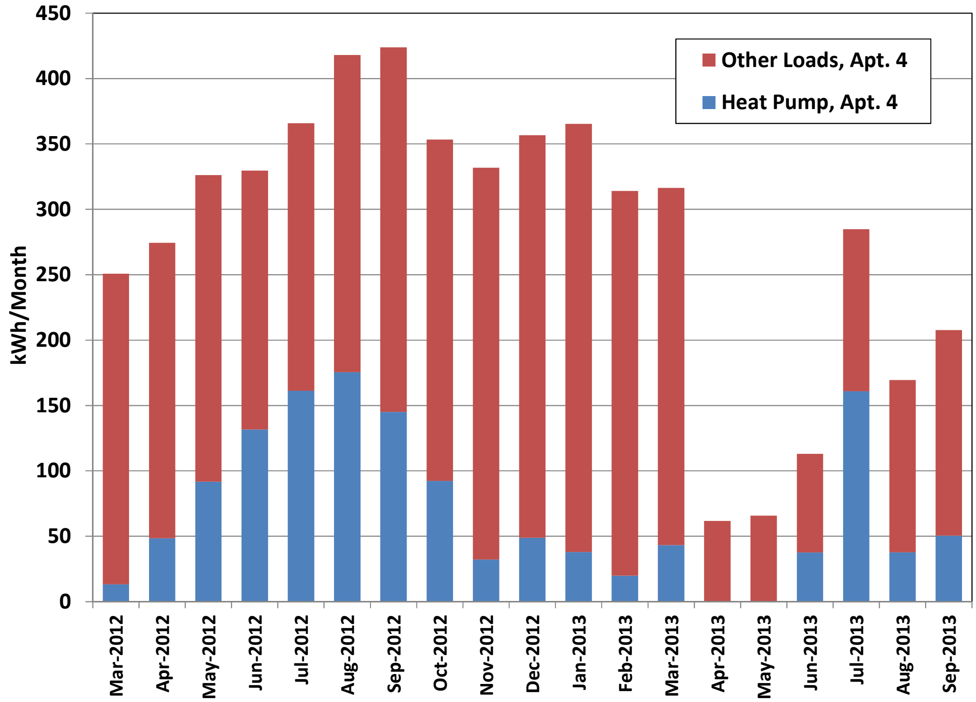

Figure 8-5 Monthly Energy Use in Apartment 4